of the field data presented here concentrates on the effect that this interaction has on the loss of wave energy. In the area where our study was conducted (see Fig. 1), the sediment concentration of the water column was not a significant factor contributing to the loss of wave energy. It has been suggested that water column sediment concentration is the key factor in the calming effect of mudbanks (Delft Hydraulics Laboratory, 1962); however, the forcing of a mud wave by wave-induced pressures is also a part of the physical processes wherever fine-grained sediments occur. An understanding of this process is important not only in the Mississippi Delta but also in such coastal areas as the Guianas, the northern coast of China, and southwest India, where extensive areas of fine-grained sediments occur.

Methods

As a cooperative research effort by scientists of the Marine Geology Branch, United States Geological Survey, Corpus Christi, Texas, and the Coastal Studies Institute, Louisiana State University, two field sites were instrumented in East Bay, Louisiana. The primary experimental station and the location of a nearby soil boring are shown in Figure 1.

Results of analysis of the boring (Fig. 2) show the bottom sediments to be very soft, recently deposited material from the Mississippi River. Shear strengths range from 1.57 kilonewtons/meter^2 (kN/m^2) near the water/sediment interface to 2.36 kN/m^2 3 meters into the sediment. These low values of shear strength are common in the Mississippi Delta. The boring log shows no evidence of the crust zone that often occurs in these sediments between -3 and -10 meters. In places where the sharp increase in shear strength that defines a crust zone occurs, it is convenient to model the physical system as a light Newtonian fluid overlying a dense, non-Newtonian fluid with a rigid bottom.

The measurement of bottom movement was complicated by two factors. First, the measurements had to be made away from a platform to ensure that the motion of natural muds would be measured. Secondly, bottom motions under typically encountered wave conditions were thought to be small, and therefore high resolution was needed. Both problems were overcome by burying accelerometers in the mud. Though displacements were around 1 cm, accelerations were such that they could be reliably measured and required no fixed reference.

Three Bruel and Kjoer type 8306 accelerometers were mounted so as to measure the accelerations in three dimensions (Fig. 3). They were placed in a water-proof cylindrical PVC housing measuring 0.215 meter in diameter and 0.635 meter in length and having a submerged weight of 5.5 kg. The housing was pushed into the mud by a diver so that the top of the package was 0.15 meter below the mud line. The electronic cable coming from the top of the package was given 4.5 meters of slack, all of which was buried in the mud, and then fixed to a taut galvanized cable that was laid along the bottom between a nearby well jacket and our main instrumented site, Platform V. Platform V, in 19.2 meters of water, is shown in Figure 4. The cable from the accelerometer was brought along the galvanized cable and up the platform leg to the recorders. The location of the accelerometer was

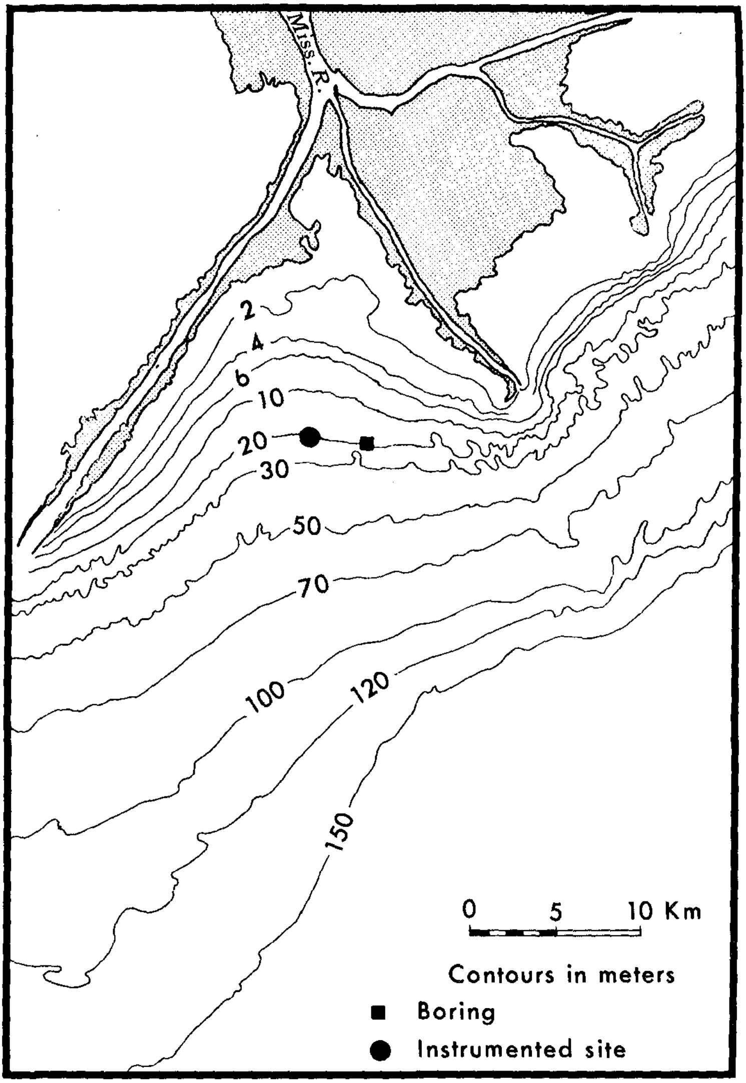

Figure 1. Location of the field site in East Bay, Louisiana.

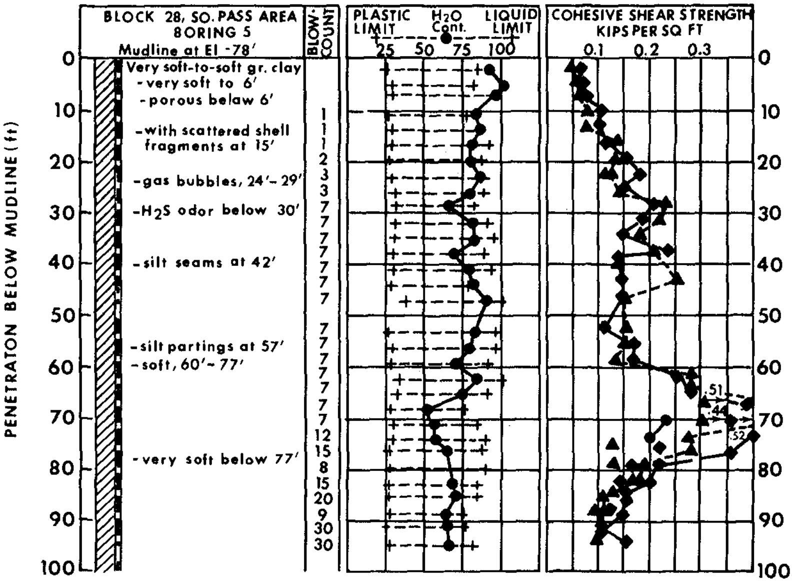

Figure 2. Results of soil boring taken near field site (1 kip/ft^2 = 48 kilonewtons/m^2). For location see Figure 1. (Boring courtesy U.S. Geological Survey, Marine Geology Branch, Corpus Christi.)

directly beneath the catwalk between the two structures so that a pressure cell attached to a weighted cable could be suspended over the package. Figure 5 is a schematic representation of the experiment and the physical system. The location of the pressure sensor was known to be within a radius of 2 meters from the accelerometer. This uncertainty in position could cause an error in the measured phase angle ϕ between the crest of the surface wave and the trough of the mud wave of $\pm 11°$ for a characteristic wave with a period of 7.75 seconds. The importance of such an error will be seen in the calculation of the dissipation of wave energy. Wave properties were measured with a wave staff, a pressure sensor, and a two-axis electromagnetic current meter attached to wire cables that were suspended from the platform and anchored to the bottom through pulleys. A system of winches and pulleys allowed us to adjust the instruments to any depth.

Platform S (see Fig. 10), 3.35 km inshore of Platform V in 5.3 meters of water, was instrumented with an anemometer, a Bendix Q-15 ducted current meter, two pressure sensors, and a wave staff. By running the instruments on Platform S simultaneously with those on Platform V it was possible to compare the net energy lost by the waves while traveling between the two data

Figure 3. Array of three accelerometers.

stations with a rate of energy loss calculated from the measurements of mud movement at Platform V.

Results

Simultaneous measurements of wave height and wave-induced pressure resulted in the data represented in Figure 6. The term n is a correction

Figure 4. The main instrumented site, Platform V.

factor that matches linear theory with observed pressures and wave heights in the manner shown (where Kp = cosh k (h + Z)/cosh kh). If the observed data were in perfect agreement with linear theory, the data points would fall along the line n equal to 1.00. Further experimentation using two pressure cells placed at different depths in the water column showed that linear theory accurately predicts the change in wave-induced pressures from near the surface to within 0.5 meter of the bottom. The fact that other researchers have obtained similar results (Hom-ma et al., 1966) supported the use of a corrected linear theory for determining surface wave heights from pressure measurements made in the water column above the accelerometer. The actual values of the correction factor n that were used were those values lying along the two least squares fit lines shown in Figure 6.

A sample of the data taken in the study is shown in Figure 7. The accelerations appear sinusoidal in form and have the same general appearance as the wave record.

The shape of the bottom pressure spectrum is similar to that of the spectrum of the vertical acceleration, and the peaks occur at the same

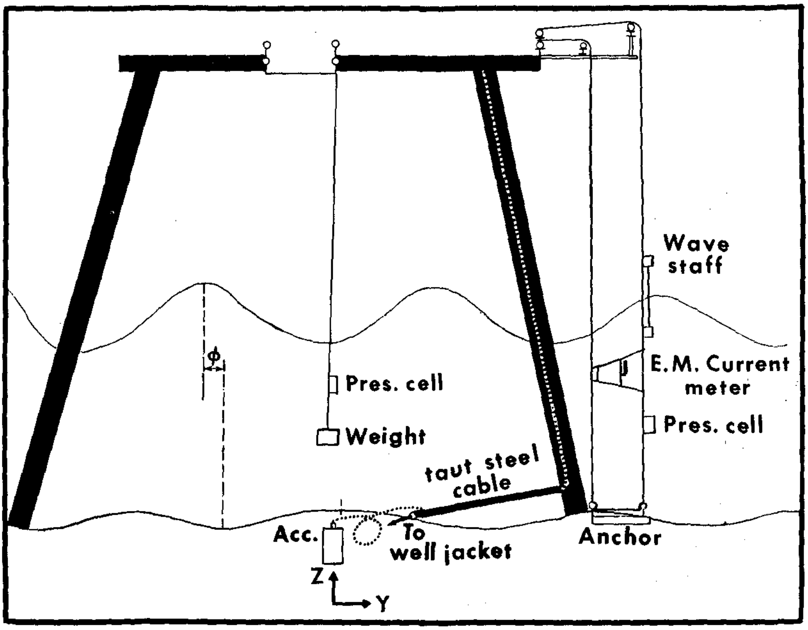

Figure 5. Experimental setup at Platform V.

frequency (Fig. 8). The low-frequency spectral components visible in the acceleration spectrum are believed to be electronic drift. (The phase angle between the crest of the mud wave and the crest of the pressure wave was 202° for the peak spectral component.) Horizontal mud motions are approximately 90° out of phase with the vertical motions, and a backward horizontal movement occurs at the crest of the bottom wave. Similar motion occurs for forced waves on an elastic half space. The ratio of vertical displacement to horizontal displacement over several sets of data averaged about 2.0.

A plot of the amplitude of the pressure wave at the bottom versus the amplitude of the mud wave (Fig. 9) reveals a roughly linear relationship for the range of pressures from near zero to 2.39×10^3 Pascal.

The average energy transmitted through the sea/sediment interface per unit and time over one wave cycle is (Gade, 1958)

$$Dm = -\frac{1}{T}\int_0^T P\,\frac{dh}{dt}\,dt \tag{1}$$

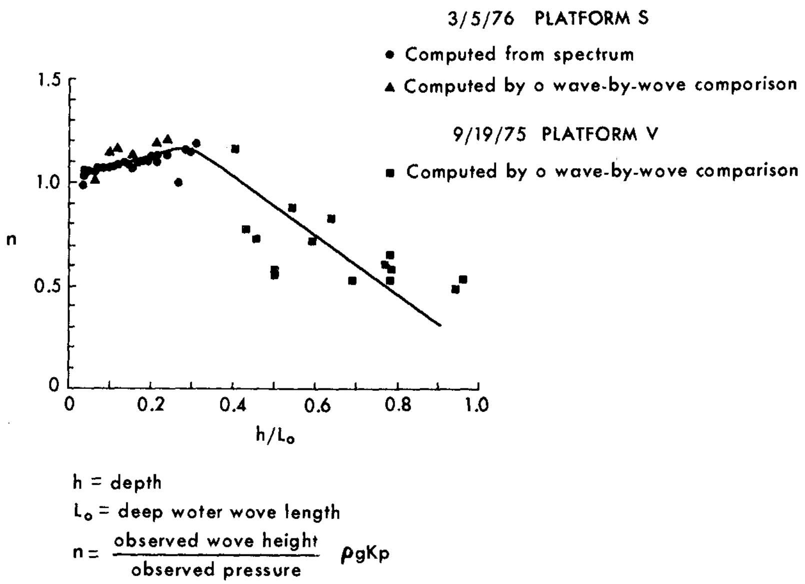

Figure 6. Comparison of observed wave height and observed wave pressure with small-amplitude wave theory.

where T = wave period
P = wave-induced bottom pressure
dh = an infinitesimal increase in the height of the interface

The general characteristics of the data show that the following functions will accurately describe the motions:

$$P = Pa + A \cos (kx - \sigma t)$$

$$h = ho + MA \cos (kx - \sigma t + \psi)$$

where Pa = steady-state bottom pressure
A = amplitude of the wave-induced bottom pressure
h_o = depth of mud over which motion occurs
M = proportionality constant between the amplitudes of the mud wave and the pressure wave
ψ = phase angle between the crest of the bottom pressure wave and the crest of the mud wave

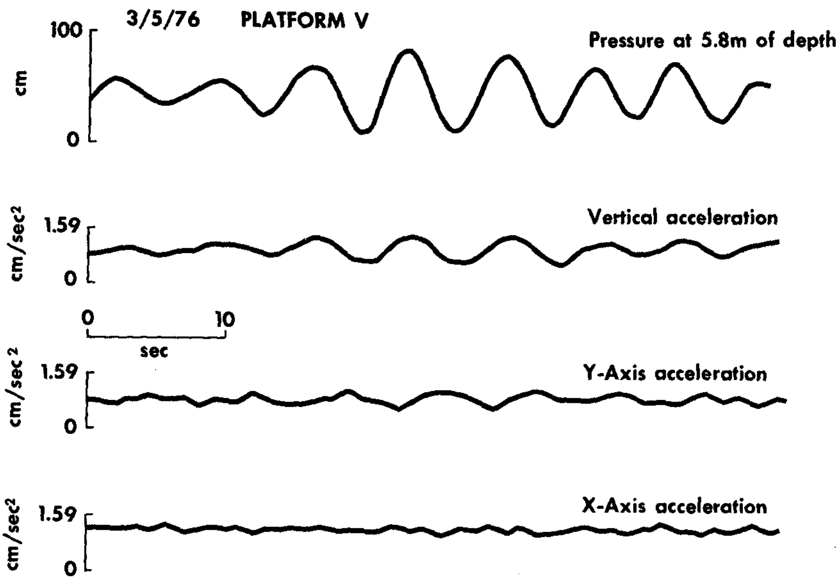

Figure 7. Sample of the data taken during the study.

After substituting equations (2) and (3) into (1) and integrating, and then using linear theory to put bottom pressures in terms of surface wave height, the equation for the rate of energy loss to the bottom is obtained:

$$Dm = \frac{\pi \rho g \; M \; H^2 \; \sin \phi}{4T \; \cosh^2 kh} \qquad (4)$$

where $\phi = 180° - \psi$.

For purposes of comparison with other theories for the dissipation of wave energy, the pressure correction factor for linear theory is not incorporated into the equation. At most this can change the energy loss rate by 20 percent. From equation (4) it can be seen that the dissipation of wave energy by the soft bottom involves only two important factors, determined by the physics of the sediment movement: (1) the relationship between the pressure force on the sediment and the resultant vertical displacement, given by M, and (2) the phase angle between the crest of the pressure wave and the trough of the mud wave, given by ϕ.

The results of the two-station experiment allowed us to estimate the energy lost from the waves. Conditions during the two-station experiment

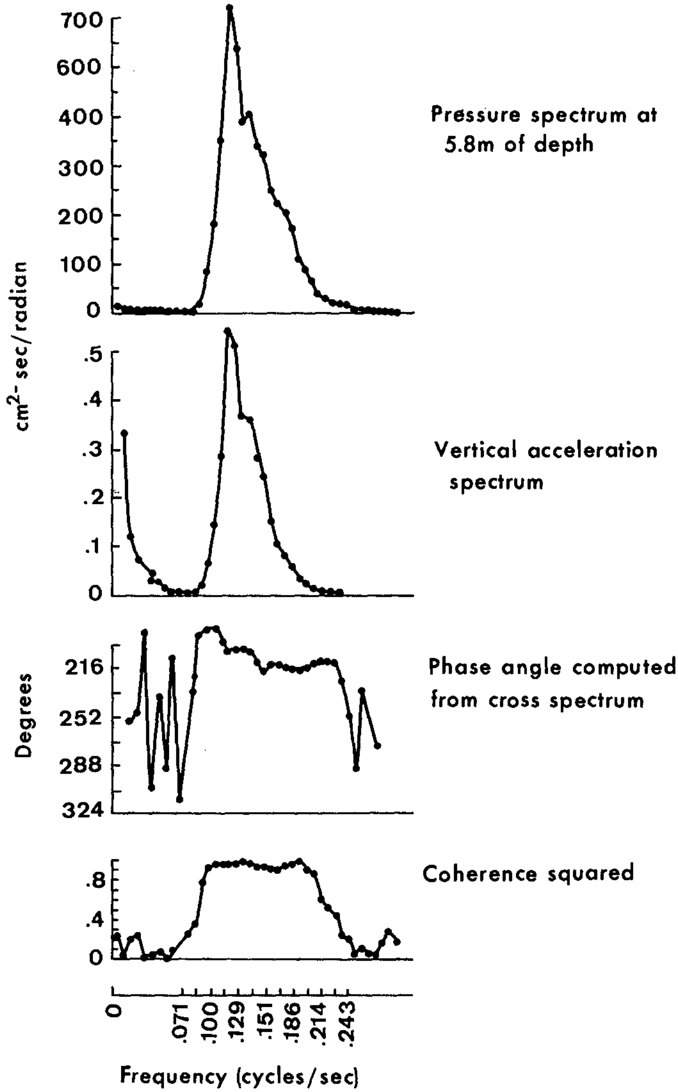

Figure 8. Results of spectral analysis of data.

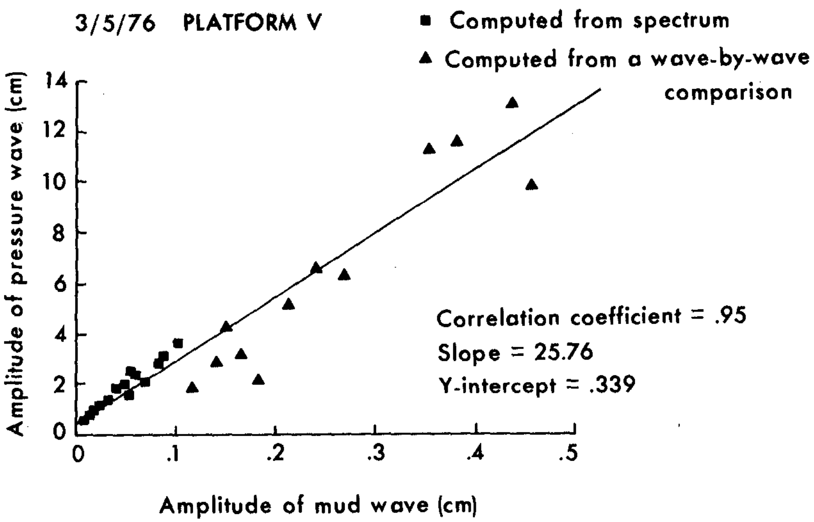

Figure 9. Amplitude of pressure wave plotted as a function of the amplitude of the mud wave.

are illustrated in Figure 10. The instruments on platform V and Platform S were run simultaneously, a procedure that resulted in a surface wave spectrum at V and at S and a bottom movement spectrum at V. For the experiment the effects of the wind, the current, and shoaling and refraction required a small correction to the measured wave height difference. The theoretical wave heights between Platforms V and S were calculated using the energy dissipation equation (4) derived for the forcing of a mud wave and taking into account shoaling and refraction based upon the period of the peak spectral component. The root mean square wave height at Platform V was used for the initial wave height. It was found that to produce agreement with the measured wave height at Platform S and keep M constant the value of the phase angle ϕ would have to be 10°.

Discussion of Results

A comparison of the results of our study with other theories for the dissipation of wave energy is shown in Figure 11. The phase angle ϕ between the crest of the surface wave and the trough of the mud wave is given two values: 22° is the angle that was actually measured at V, and 10° is the angle that results in the correct average dissipation of wave energy between Platforms V and S, assuming that M is constant. Note that the use of the smaller angle does not significantly reduce the magnitude of the dissipation